

Testing the meson cloud in the nucleon in Drell-Yan processes

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Abstract

We discuss the present status of the $\bar{u} - \bar{d}$ asymmetry in the nucleon and analyze the quantities which are best suited to verify the asymmetry. We find that the Drell-Yan asymmetry is the quantity insensitive to the valence quark distributions and very sensitive to the flavour asymmetry of the sea. We compare the prediction of the meson cloud model with different experimental data including the Fermilab E772 data and recent data of the NA51 Collaboration at CERN and make predictions for the planned Drell-Yan experiments.

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I. INTRODUCTION

The deviation of the Gottfried Sum Rule from its classical value [1]

$$S_G = \int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = \frac{1}{3} \quad (1)$$

observed by the New Muon Collaboration (NMC) at CERN [2,3] has created a large interest on the possible sources of the violation. In the NMC experiment the neutron structure function which enters the sum rule is deduced from deep inelastic scattering off deuterium. It could be biased by nuclear two-body effects which were ignored in the NMC analysis. While shadowing effects [4–7] cause the real value of the Gottfried Sum Rule to be even smaller than the value given by NMC, the anti-shadowing effect, due to the presence of virtual mesons which bound the deuteron, tends to restore the classical value [8,7]. A recent unfolding of the shadowing and anti-shadowing effects [7] suggest, however, a genuine violation. This can be understood as consequence of an internal asymmetry $\bar{d} > \bar{u}$ of the quarks in the proton (the opposite asymmetry is expected for the neutron if the proton-neutron charge symmetry holds). The asymmetry has been confirmed recently by the NA51 collaboration group at CERN [9]. Since at large Q^2 the perturbative QCD evolution is flavour independent and, to leading order in $\log Q^2$, generates equal number of $\bar{u}u$ and $\bar{d}d$ sea quarks nonperturbative effects must play an important role here. The effect of the asymmetry has been predicted by the models in which the physical nucleon contains an admixture of the πN and $\pi \Delta$ components in the Fock expansion [10]. The predicted effect of the asymmetry agrees [11] with that deduced from the NA51 experiment.

The idea of the $\bar{u} - \bar{d}$ asymmetry is not new. It was considered a decade ago by Ito et al. [12] as a possible explanation for the slope of the rapidity distribution of dilepton production in the proton-Pt collision at Fermilab. An alternative interpretation stimulated by the discovery of the EMC effect invoked the enhancement of the nuclear sea in Pt with respect to a collection of free nucleons [13]. In general both effects can coexist.

In the advent of high precision data on the dilepton production in the proton-proton and proton-deuteron scattering [14], it is interesting to review the present status of our knowlegde

on the $\bar{u} - \bar{d}$ asymmetry. We will discuss the quantities which should most unambiguously confirm the asymmetry and allow for verification of different theoretical concepts. We also confront the prediction of the meson cloud model with the existing data.

II. GOTTFRIED SUM RULE

The Gottfried Sum Rule [1] (GSR) addresses the value of the integral over x of the difference of the $F_2(x)$ structure function of the proton (p) and neutron (n). It is written¹ as

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = \int_0^1 \frac{4}{9} [u_p^v(x) - u_n^v(x)] + \frac{1}{9} [d_p^v(x) - d_n^v(x)] + 2 \left\{ \frac{4}{9} [\bar{u}_p(x) - \bar{u}_n(x)] - \frac{1}{9} [\bar{d}_p(x) - \bar{d}_n(x)] \right\} dx, \quad (2)$$

where $u_p^v(x) \equiv u_p(x) - \bar{u}_p(x)$, etc. Baryon number conservation reduces the expression further to

$$S_G = \frac{1}{3} + \int_0^1 \frac{8}{9} [\bar{u}_p(x) - \bar{u}_n(x)] - \frac{2}{9} [\bar{d}_p(x) - \bar{d}_n(x)] dx. \quad (3)$$

As seen from Eq.(3) the valence quarks do not influence the Gottfried Sum Rule violation although they are of crucial importance for the GSR integrand. Assuming further charge symmetry for the nucleon sea, i.e., $\bar{u}_p(x) = \bar{d}_n(x)$, etc. and making the customary assumption that $\bar{u}_p(x) = \bar{d}_p(x)$, one finds the classical value of 1/3. The NMC experiment [2] of the relevant structure functions, over the interval $0.004 \leq x \leq 0.8$, yielded when extrapolated to $0 \leq x \leq 1$,

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = 0.24 \pm 0.016, \quad (4)$$

at $Q^2 = 5 \text{ GeV}^2$. It should be noted that QCD corrections do not play any role here. While the leading order corrections to the Gottfried Sum Rule cancel, the higher order corrections are negligibly small.

The integrand of the Gottfried Sum Rule has been obtained from the ratio $R = F_2^n/F_2^p$ and the deuteron F_2^d structure function

¹The structure functions $F_2(x)$ and the quark distribution functions $q(x)$ are, of course, functions of Q^2 . However, the Q^2 dependence is suppressed to keep the expressions from being too cumbersome.

$$F_2^p(x) - F_2^n(x) = 2F_2^d(x) \frac{1 - R(x)}{1 + R(x)} . \quad (5)$$

In the first evaluation of GSR the deuteron structure function was taken from a global fit to the results of earlier experiments. In the meantime NMC has published values of F_2^p and F_2^d of its own accurate measurements at low x [15]. The old value of GSR [2] has been updated [3] to

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = 0.235 \pm 0.026 . \quad (6)$$

The total error here is larger than in (4) due to a more extensive examination of the systematic uncertainties. The quoted error bar does not include the effects of shadowing and antishadowing.

In the most general case not only the so-called $SU(2)_Q$ [16] charge-symmetry is violated but also the isospin symmetry between proton and neutron $SU(2)_I$. In this case the antiquark distributions in proton and neutron can be expressed as:

$$\begin{aligned} \bar{u}_p(x) &= \bar{q}(x) - \frac{1}{2}\Delta_Q(x) - \frac{1}{2}\Delta_I(x) , \\ \bar{d}_p(x) &= \bar{q}(x) + \frac{1}{2}\Delta_Q(x) - \frac{1}{2}\Delta_I(x) , \\ \bar{u}_n(x) &= \bar{q}(x) + \frac{1}{2}\Delta_Q(x) + \frac{1}{2}\Delta_I(x) , \\ \bar{d}_n(x) &= \bar{q}(x) - \frac{1}{2}\Delta_Q(x) + \frac{1}{2}\Delta_I(x) . \end{aligned} \quad (7)$$

The signs in front of $\Delta_Q(x)$ and $\Delta_I(x)$ have been chosen to assure positivity of Δ_Q and Δ_I in the case the asymmetries give the effect required by the NMC result. With the parameterization (7) the Gottfried Sum Rule (3) can be written as

$$S_G = \frac{1}{3} - \frac{2}{3}\Delta_Q - \frac{10}{9}\Delta_I . \quad (8)$$

The factor 10/9 shows the sensitivity to the $SU(2)_I$ symmetry violation. The violation of the Gottfried Sum Rule exclusively via breaking the $SU(2)_Q$ symmetry requires $\Delta_Q = 0.14 \pm 0.03$. On the other hand violation of GSR exclusively via breaking the $SU(2)_I$ symmetry requires $\Delta_I = 0.08 \pm 0.02$.

It has been argued in Ref. [17] that both the effects of asymmetric $SU(2)$ sea and the proton-neutron isospin symmetry breaking will be very difficult to disentangle as they may, in general, lead to very much the same behaviour both in deep inelastic scattering and Drell-Yan processes. A careful analysis [16] based on the σ -term and scale Ward identity suggests rather $\Delta_Q \gg \Delta_I$. Therefore in the further analysis we will neglect the effect of the $SU_I(2)$ symmetry violation.

Since the standard Altarelli-Parisi [18] evolution equations generate equal number of $\bar{u}u$ and $\bar{d}d$ pairs, one does not expect strong scale dependence of the GSR. The two-loop evolution gives a rather negligible effect [19]. The Pauli exclusion principle leads to some interference phenomena which produces only a small asymmetry [19].

The answer likely lies with more complicated nonperturbative physics. The presence of the pion cloud in the nucleon gives a natural explanation of the excess of \bar{d} over \bar{u} . It has been extensively analyzed in a series of papers [20–26] with the result for the GSR being dependent on the details of the model, especially on vertex form factors. Restricting the form factors by fitting to the cross sections for high-energy production of neutrons and Δ^{++} yields the GSR [25,10,27] in rough agreement with that obtained by NMC [2,3].

The flavour content of the sea in the nucleons can be tested in Drell-Yan experiments, which is the subject of the present paper. In the first phenomenological analyses the anti-quark distributions were typically defined as

$$\bar{u}(x) = \bar{q}(x) - \frac{1}{2}\Delta(x) \quad \text{and} \quad \bar{d}(x) = \bar{q}(x) + \frac{1}{2}\Delta(x) . \quad (9)$$

Different assumptions on $\Delta(x)$ lead to different predictions for the Drell-Yan production rate. For instance, the initial parameterization [28] used $\Delta(x) = A(1-x)^k$, which placed the $\bar{d}-\bar{u}$ difference at large x ($x > 0.05$), led to very large values for $\bar{d}_p(x)/\bar{u}_p(x)$ for $x \geq 0.1$. These large ratios have been ruled out by a recent reanalysis of earlier Drell-Yan data [29]. More recent [30] parameterizations have a form $\Delta(x) = A_\Delta x^\eta (1-x)^{\eta_s} (1+\gamma x)$, which places the bulk of the difference at smaller x .

It is expected that future QCD lattice gauge calculations will be able to generate the

quark structure of the nucleon and evaluate the $\overline{d}_p(x)$ and $\overline{u}_p(x)$ distributions. At present one has to rely on phenomenological models consistent with our knowledge in other branches of hadronic physics. The meson cloud model [31,27] seems to satisfy this criterion. Furthermore it is worth mentioning in this context that importance of pion loop effects for nucleon properties has been demonstrated in a recent lattice QCD calculation [32].

III. MESON CLOUD MODEL OF THE NUCLEON

In this section we briefly sketch the meson cloud model (MCM) of the nucleon [26,31,27] and present its prediction for the asymmetry of the light sea antiquarks. In this model the nucleon is viewed as a quark core, termed a bare nucleon, surrounded by the mesonic cloud. The nucleon wave function can be schematically written as a superposition of a few principle Fock components (only πN and $\pi\Delta$ are shown explicitly)

$$\begin{aligned}
|p\rangle_{phys} = \sqrt{Z} & \left[|p\rangle_{core} \right. \\
& + \int dy d^2\vec{k}_\perp \phi_{N\pi}(y, \vec{k}_\perp) \left(\sqrt{\frac{1}{3}} |p\pi^0; y, \vec{k}_\perp\rangle + \sqrt{\frac{2}{3}} |n\pi^+; y, \vec{k}_\perp\rangle \right) \\
& + \int dy d^2\vec{k}_\perp \phi_{\Delta\pi}(y, \vec{k}_\perp) \left(\sqrt{\frac{1}{2}} |\Delta^{++}\pi^-; y, \vec{k}_\perp\rangle - \sqrt{\frac{1}{3}} |\Delta^+\pi^0; y, \vec{k}_\perp\rangle + \sqrt{\frac{1}{6}} |\Delta^0\pi^+; y, \vec{k}_\perp\rangle \right) \\
& \left. + \dots \right].
\end{aligned} \tag{10}$$

with Z being the wave function renormalization constant which can be calculated by imposing the normalization condition $\langle p|p\rangle = 1$. The $\phi(y, \vec{k}_\perp)$'s are the light cone wave functions of the πN , $\pi\Delta$, etc. Fock states, y is the longitudinal momentum fraction of the π (meson) and \vec{k}_\perp its transverse momentum.

It can be expected that the structure of the bare nucleon (core) is rather simple. Presumably, it can be described as a three quark system in the static limit. Of course, in the deep inelastic regime at higher Q^2 additional sea of perturbative nature is created unavoidably by the standard QCD evolution.

The model includes all the mesons and baryons required in the description of the low energy nucleon-nucleon and hyperon-nucleon scattering, i.e. the π , K , ρ , ω , K^* and the N , Λ , Σ , Δ and Σ^* . In contrast to other approaches in the literature the model ensures charge conservation, baryon number and momentum sum rules [31] by construction.

The main ingredients of the model are the vertex coupling constants, the parton distribution functions for the virtual mesons and baryons and the vertex form factors which account for the extended nature of the hadrons. The coupling constants are assumed to be related

via $SU(3)$ symmetry which seems to be well established from low-energy hyperon-nucleon scattering.

It was suggested in Ref. [25] to use the light cone meson-baryon vertex form factor

$$F(y, k_\perp^2) = \exp \left[-\frac{M_{MB}^2(y, k_\perp^2) - m_N^2}{2\Lambda_{MB}^2} \right], \quad (11)$$

where k_\perp is the transverse momentum of the meson and $M_{MB}(y, k_\perp^2)$ is the invariant mass of the intermediate two-body meson-baryon Fock state,

$$M_{MB}^2(y, k_\perp^2) = \frac{m_B^2 + k_\perp^2}{1-y} + \frac{m_M^2 + k_\perp^2}{y}. \quad (12)$$

By construction, such form factors assure the momentum sum rule [25,31]. The parameters Λ_{MB} are the principal nonperturbative parameters of the model. They have been determined from an analysis of the $p \rightarrow n, \Delta, \Lambda$ fragmentation spectra [27] using light cone flux functions [27] ($\Lambda_{\pi N}^2 = 1.08 \text{ GeV}^2$ and $\Lambda_{\pi \Delta}^2 = 0.98 \text{ GeV}^2$). With these parameters the pion exchange model gives a very good description of the spectra.

In practice the probability of the Fock components with strange particles is rather small. For instance the probability to find a $K\Lambda$ state in the nucleon is about 1%, whereas the probability to find a πN state is 0.18. In all applications in the present paper the higher Fock states involving strange particles can be neglected.

The x dependence of the structure functions in the meson cloud model can be written as a sum of components corresponding to the expansion given by Eq.(10).

$$F_2^N(x) = Z \left[F_{2,core}^N(x) + \sum_{MB} \left(\delta^{(M)} F_2(x) + \delta^{(B)} F_2(x) \right) \right]. \quad (13)$$

The contributions from the virtual mesons can be written as a convolution of the meson (baryon) structure functions and its longitudinal momentum distribution in the nucleon [33]

$$\delta^{(M)} F_2(x) = \int_x^1 dy f_M(y) F_2^M\left(\frac{x}{y}\right). \quad (14)$$

The same is true for the virtual baryons

$$\delta^{(B)} F_2(x) = \int_x^1 dy f_B(y) F_{2,core}^B\left(\frac{x}{y}\right). \quad (15)$$

In a natural way $f_M(y)$ and $f_B(y)$ are related via [31]

$$f_B(y) = f_M(1 - y) . \quad (16)$$

Eq. (14) (and also Eq. 15) can be written in an equivalent form in terms of the quark distribution functions

$$\delta^{(M)} q_f(x) = \int_x^1 f_M(y) q_f^M\left(\frac{x}{y}\right) \frac{dy}{y} . \quad (17)$$

The longitudinal momentum distributions (splitting functions, flux factors) of virtual mesons (or baryons) can be calculated assuming a model of the vertex and depend on the coupling constants and vertex form factors. Further details can be found in Refs. [31,27].

The parton distributions "measured" in pion-nucleus Drell-Yan processes [34] are used for the mesons. The deep-inelastic structure functions of the bare baryons, $F_{2,core}^N(x, Q^2)$, $F_{2,core}^B(x, Q^2)$ are in principle unknown. In practical calculations it is usually assumed $F_{2,core}^N(x, Q^2) = F_{2,phys}^N(x, Q^2)$ [22,35], which is not fully consistent. Recently [36], we have extracted $F_{2,core}^N$ by fitting the quark distributions in the bare nucleon, together with (parameter-free) mesonic corrections, to the experimental data on deep-inelastic scattering:

(a) $F_2^p(x, Q^2) - F_2^n(x, Q^2)$ [3],

(b) $F_2^n(x, Q^2)/F_2^p(x, Q^2)$ [3],

(c) $F_3^{\nu N}(x, Q^2)$ [37],

(d) $\bar{q}(x, Q^2)$ [38].

The following simple parameterization has been used for the quark distributions in the bare proton at the initial scale $Q_0^2 = 4 \text{ (GeV/c)}^2$. Note, that we have used $\bar{u}-\bar{d}$ symmetric sea quark distribution for the core.

$$xu_{v,core}(x, Q_0^2) = N_u x^{0.38} (1 - x)^{2.49} (1 + 10.5x) , \quad (18)$$

$$xd_{v,core}(x, Q_0^2) = N_d x^{0.07} (1 - x)^{4.63} (1 + 150x) ,$$

$$xS_{core}(x, Q_0^2) = 0.17(1 - x)^{13.8} ,$$

where

$$S_{core} = u_{s,core} = \overline{u}_{s,core} = d_{s,core} = \overline{d}_{s,core} = 2s_{s,core} = 2\overline{s}_{s,core}. \quad (19)$$

The details of the fit and a comprehensive discussion of DIS will be given in Ref. [36]. An example of the fit to $F_2^p(x) - F_2^n(x)$ is shown in Fig.1. The resulting total sea quark distribution is compared in Fig.2 with an experimental sea quark distribution obtained from (anti)neutrino induced reactions [38]. The so-extracted parameterization of the quark distributions in the bare baryons can be used to calculate the cross-sections for both the lepton deep-inelastic scattering and for the Drell-Yan processes. In the present article we will present predictions(!) for the Drell-Yan dilepton production in elementary nucleon-nucleon collisions as well as for the nucleon-nucleus collisions.

IV. DRELL-YAN PROCESSES

The Drell-Yan process [39] involves the electromagnetic annihilation of a quark (antiquark) from the incident hadron A with an antiquark (quark) in the target hadron B . The resultant virtual photon materializes as a dilepton pair ($\ell^+\ell^-$) with muons being the pair most readily detected in experiments.

Ellis and Stirling have shown that the measurement of Drell-Yan cross sections in the proton-proton and proton-deuteron collisions provides information on the $\bar{d}_p(x)/\bar{u}_p(x)$ ratio [28].

The cross section for the DY process can be written as

$$\frac{d\sigma^{AB}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1 x_2} K(x_1, x_2) \sum_f e_f^2 \left[q_A^f(x_1) \bar{q}_B^f(x_2) + \bar{q}_A^f(x_1) q_B^f(x_2) \right], \quad (20)$$

where s is the square of the center-of-mass energy and x_1 and x_2 are the longitudinal momentum fractions carried by the quarks of flavour f . The $q_A^f(x_1)$ ($\bar{q}_A^f(x_1)$) and $q_B^f(x_2)$ ($\bar{q}_B^f(x_2)$) are the (anti-)quark distribution functions of the beam and target, respectively. The factor $K(x_1, x_2)$ accounts for the higher-order QCD corrections that enter the process. Its value over the kinematic range where experiments are carried out is typically 1.5. The values of x_1 and x_2 are extracted from experiment via

$$M^2 = sx_1 x_2 \approx 2P_{\ell^+} P_{\ell^-} (1 - \cos \theta_{\ell^+ \ell^-}), \quad (21)$$

where M is the mass of the dilepton pair, P_{ℓ^+} and P_{ℓ^-} are the laboratory momenta of the leptons, and $\theta_{\ell^+ \ell^-}$ is the angle between their momenta vectors. The total longitudinal momentum of the lepton pair $(P_{\ell^+} + P_{\ell^-})_L$ fixes $x_1 - x_2$ via

$$x_1 - x_2 \equiv x_F = \frac{2(P_{\ell^+} + P_{\ell^-})_L}{s} - 1. \quad (22)$$

In order to avoid spurious contributions to the DY yield from vector meson decays, all measurements are made for $M > 4 \text{ GeV}$, and the region $9 \leq M \leq 11 \text{ GeV}$ is excluded to avoid the Υ resonances.

The absolute value of the Drell-Yan cross section is biased by the uncertainty in extrapolating from time-like to space-like values of Q^2 when relating the Drell-Yan with deep-inelastic scattering which involves the factor K (see Eq.20). In order to avoid the uncertainty it is desirable to consider ratios [13,28,10] rather than the absolute cross sections. Whether the K -factors for the pp and pn collisions are identical can be checked by calculating higher-order QCD corrections. In Fig.3 we show the K -factors calculated according to the formalism developed in Ref. [34] for two different leading order quark distributions [40,41]. Although the K -factor depends on the input quark distribution as well as on x_1 and x_2 its value is practically identical for proton-proton and proton-neutron collisions. The approximate equality $K_{pp} = K_{pn}$ allows us to neglect the higher order corrections and limit ourselves to the much simpler leading order analysis.

The quark distributions found from the procedure described in the former section can be further tested by comparison with the Drell-Yan E772 data [29] for the differential cross section $M^3 d^2\sigma/dx_F dM$ for the dilepton production in the $p + d$ collision. By fitting the K -factors the result of the calculation can be compared with the experimental data. In order to check the sensitivity to the $\bar{u} - \bar{d}$ asymmetry we have also performed the calculation with symmetrized sea:

$$u_s(x) = \bar{u}_s(x) = d_s(x) = \bar{d}_s(x) = \frac{\bar{u}(x) + \bar{d}(x)}{2} . \quad (23)$$

In Fig.4 we show the result of the fit for our original model (solid line, $\chi^2/N = 1.15$) and the results obtained with the symmetrized (Eq. 23) sea distribution (dashed line, $\chi^2/N = 1.42$). Although there is some sensitivity to the $\bar{d} - \bar{u}$ asymmetry, it can be easily compensated by a slightly different normalization factor. For comparison we also show the result obtained with the $MSR(S'_0)$ quark distributions (dash-dotted line, $\chi^2/N = 1.84$).

The present experimental data for the Drell-Yan processes in the elementary nucleon-nucleon collisions suffer from rather low statistics. Therefore at present one is forced to compare a theoretical calculation with the proton-nucleus experimental data. In the first approximation the cross section for the production of the dilepton pairs in the proton-nucleus

scattering can be expressed in terms of the elementary pp and pn processes as

$$\sigma_{pA}^{DY} = Z\sigma_{pp}^{DY} + N\sigma_{pn}^{DY} . \quad (24)$$

It has been shown [42,10] that the ratio of the cross section for the scattering of protons from the nucleus with $N - Z \neq 0$ to that from an isoscalar target such as deuterium is sensitive to the $\bar{d}_p(x) - \bar{u}_p(x)$ difference. These ratios have been measured by the E772 Collaboration at FNAL [42] for carbon, calcium, iron and tungsten targets. Neglecting nuclear effects, elementary algebra leads to the following result for the ratio

$$R_{DY} = \frac{2\sigma^{DY}(p+A)}{A\sigma^{DY}(p+d)} = \frac{2Z}{A} + \frac{N-Z}{A} \frac{2\sigma^{pn}(x_1, x_2)}{\sigma^{pp}(x_1, x_2) + \sigma^{pn}(x_1, x_2)}, \quad (25)$$

where Z , N , A are number of protons, neutrons and the atomic number, respectively. In the large x_2 (target) limit the ratio takes a very simple form [29]:

$$R_{DY}(x) = 1 + \frac{N-Z}{A} \frac{\Delta(x)}{\bar{u}(x) + \bar{d}(x)}, \quad (26)$$

showing that the Drell-Yan processes with non-isoscalar targets are relevant for the issue of the asymmetry.

The experimental ratios are consistent with symmetric quark distributions [29,42] (see Fig.5), which renders those data useless for establishing the asymmetry. Moreover, using asymmetric quarks distribution functions (solid and dashed lines) has a rather small effect on the ratio. The ratio obtained with the recent $MSR(A)$ quark distributions [30] almost coincides with the result of our model. As seen from the figure these ratios do not provide a test sensitive enough.

An alternative idea to study the asymmetry was proposed more than a decade ago by Ito et al. [12]. They have suggested to analyze the logarithmic derivative of the rapidity distribution

$$S(\sqrt{\tau}) = \frac{d}{dy} \ln \frac{d^2\sigma}{dMdy} \Big|_{y=0}, \quad \text{with } \tau = x_1 x_2, \quad (27)$$

where $y = \ln(x_1/x_2)/2$ is the rapidity. This quantity also possesses the desired property of being independent of the K -factor. In terms of the quark distributions the slope can be expressed as

$$S(x) = \frac{x^2}{X(x, x)} \left(\left. \frac{\partial}{\partial x_1} X(x_1, x) \right|_{x_1=x} - \left. \frac{\partial}{\partial x_2} X(x, x_2) \right|_{x_2=x} \right) , \quad (28)$$

where

$$\begin{aligned} X(x_1, x_2) = & \frac{4}{9} \left\{ u(x_1) \left[\frac{Z}{A} \bar{u}(x_2) + \frac{N}{A} \bar{d}(x_2) \right] + \bar{u}(x_1) \left[\frac{Z}{A} u(x_2) + \frac{N}{A} d(x_2) \right] \right\} \\ & + \frac{1}{9} \left\{ d(x_1) \left[\frac{Z}{A} \bar{d}(x_2) + \frac{N}{A} \bar{u}(x_2) \right] + \bar{d}(x_1) \left[\frac{Z}{A} d(x_2) + \frac{N}{A} u(x_2) \right] \right\} \\ & + \frac{1}{9} \left\{ s(x_1) \bar{s}(x_2) + \bar{s}(x_1) s(x_2) \right\} . \end{aligned} \quad (29)$$

We illustrate the effect of the $\bar{u} - \bar{d}$ asymmetry on the slope of the rapidity distribution in Fig.6. Here the solid lines are calculated using the asymmetric quark distribution of the recent $MSR(A)$ quark parameterization [30] and those obtained from our meson model [27,31,36]. The dashed lines are obtained by using symmetrized quark distributions given by Eq.(23). The arrows show the effect of the symmetrization which decreases the slope. In this and all following calculations we have included corrections due to the Q^2 scale changing ($Q^2 = sx_1x_2$) by employing leading log Altarelli-Parisi QCD evolution. It has turned out that the resulting effects of the evolution are rather small.

The rapidity slope (see Eq. 27) is a quantity which is sensitive not only to the $\bar{u} - \bar{d}$ asymmetry but also to valence quark distributions. In Fig.7 we display the slope of the rapidity distribution calculated with different quark distributions. The solid line is the result of our meson model [36]. The dotted line is the result obtained with the Owens parameterization [40] of the quark distributions, the dashed line was obtained with the recent $MRS(A)$ parameterization [30] with $\bar{u} - \bar{d}$ asymmetry and the dash-dotted line was obtained with $MRS(S'_0)$ [41] (symmetric) distribution. Fig.7 clearly demonstrates that the asymmetry is not the only ingredient and a reasonable description of the experimental data [12] can be obtained with both flavour symmetric and asymmetric distributions.

In obtaining both Eq.(25) and Eq.(28) we have neglected completely all nuclear effects like Fermi-motion, nuclear binding, excess pions or shadowing. Although they are predominantly flavour symmetric, it is obvious that they can modify the conclusions drawn based on the nuclear data. An information on nuclear effects can result only from the comparison

of the slopes for a nuclear target and for a deuteron one. It seems essential in the future to analyze more elementary processes, i.e. dilepton production in the proton-proton and proton-deuteron collisions. In the following we shall concentrate on those reactions as most reliable source of the information on the flavour asymmetry of the sea quarks.

A quantity which can be extracted almost directly from the experiment is

$$A_{DY}(x_1, x_2) = \frac{\sigma_{pp}(x_1, x_2) - \sigma_{pn}(x_1, x_2)}{\sigma_{pp}(x_1, x_2) + \sigma_{pn}(x_1, x_2)} , \quad (30)$$

which we will call Drell-Yan asymmetry. In formula (30) σ_{pp} and σ_{pn} are the cross sections for the dilepton production in the proton-proton and proton-neutron scattering. The Drell-Yan asymmetry (30) can be expressed in terms of \bar{q} and Δ introduced in Eq.(9)

$$A_{DY}(x_1, x_2) = \frac{[u(x_2) - d(x_2)][3\bar{q}(x_1) - 5/2\Delta(x_1)] - [4u(x_1) - d(x_1)]\Delta(x_2)}{[u(x_2) + d(x_2)][5\bar{q}(x_1) - 3/2\Delta(x_1)] + [4u(x_1) + d(x_1)]2\bar{q}(x_2)} . \quad (31)$$

In the case of flavour symmetric sea ($\Delta = 0$) it is natural to expect that $A_{DY} > 0$ since $u > d$. The sign of A_{DY} can be, however, reversed by increasing the flavour asymmetry of the proton sea ($\Delta > 0$).

Two-dimensional maps of the Drell-Yan asymmetry as a function of x_1 and x_2 are shown in the form of the contour plots in Fig.8. The different maps were obtained with the Owens parameterization [40] (left-upper corner), symmetric MRS(S'_0) [41] (right-upper corner), the new MRS(A) [30] with the $\bar{u} - \bar{d}$ asymmetry built in (left-lower corner) and the prediction of the meson cloud model [27,31,36] (right-lower corner). The result obtained with the Owens (symmetric) parameterization and symmetric MRS(S'_0) parameterization are quite similar. This clearly demonstrates that the asymmetry A_{DY} is the desired quantity – insensitive to the valence quark distributions. It is also worth noting here that A_{DY} is positive in the whole range of (x_1, x_2) . How the $\bar{u} - \bar{d}$ asymmetry influences A_{DY} is shown in two lower panels. It is very promising that A_{DY} obtained with the asymmetric quark distributions (lower panels) differs considerably (please note the change of sign in the lower panels) from the result obtained with symmetric distribution (upper panels) and this should make an unambiguous verification of the flavour asymmetry of the sea quarks possible. It is not

random in our opinion that the result obtained within the meson cloud model is very similar to that obtained from the parameterization fitted to different experimental data. We stress in this context that A_{DY} calculated in the meson cloud model is fairly insensitive to the quark distributions in the bare nucleons (baryons). It is primarily sensitive to the $\bar{u} - \bar{d}$ asymmetry which is fully determined by the quark distributions in pions (mesons), taken here from the pion-nucleus Drell-Yan processes. We have assumed that the quark distributions in other mesons are related to those for the pion via $SU(3)_f$ symmetry.

Following the suggestion of Ellis and Stirling, the NA51 Collaboration at CERN has measured recently the A_{DY} asymmetry along the $x_1 = x_2$ diagonal [9]. Due to low statistics only A_{DY} at low $x = x_1 = x_2$ was obtained. In Fig.9 we show their experimental result (one experimental point) together with the results obtained with different quark distributions. The meaning of the lines here is the same as in Fig.6. The result denoted as MCM, obtained within the meson cloud model [31,27,36] essentially without free parameters, nicely agrees with the experimental data point. In order to better understand the result and the relation to the $\bar{u} - \bar{d}$ asymmetry let us express the cross sections in Eq.(30) in terms of the quark distributions. Assuming proton-neutron isospin symmetry and taking $x_1 = x_2 = x$ as for the NA51 experiment one gets in terms of the quark distributions in the proton

$$A_{DY} = \frac{5(u - d)(\bar{u} - \bar{d}) + 3(u\bar{u} - d\bar{d})}{5(u + d)(\bar{u} + \bar{d}) + 3(u\bar{u} - d\bar{d}) + 4(s\bar{s} + 4c\bar{c})}. \quad (32)$$

Let us consider first the case $\bar{u} = \bar{d}$. For a crude estimation one may neglect sea-sea terms (important at small x only) and assume $u_{val}(x) = 2d_{val}(x)$, which leads to $A_{DY} = 1/11 > 0$. The same crude estimate in the case of asymmetric sea in conjunction with decomposition Eq.(9) yields

$$A_{DY} = \frac{-19\Delta + 6\bar{q}}{-9\Delta + 66\bar{q}}. \quad (33)$$

This demonstrates a strong sensitivity both on $\bar{d} - \bar{u}$ asymmetry and on the absolute normalization of the sea. The lack of dependence on the valence quark distributions in the approximate Eq.(33) suggests a weak dependence in the exact formula Eq.(32). The negative value obtained by NA51 experiment $A_{DY} = -0.09 \pm 0.02 \pm 0.025$ automatically implies

$\bar{d} > \bar{u}$ at least for the measured $x = 0.18$ (provided that the proton-neutron isospin symmetry violation is small(!)). The data point of the NA51 group is up to now the most direct evidence for the flavour asymmetry of the sea quarks, which is explicitly shown in Fig.10 where A_{DY} has been translated into the ratio of $\bar{u}(x)/\bar{d}(x)$. The x dependence of the asymmetry is awaiting further experiments. It is expected that the new experiment planned at Fermilab [14] will be very useful in this respect and will provide the x dependence of the $\bar{u} - \bar{d}$ asymmetry up to $x = 0.4$ and will shed new light on the microscopic structure of the nucleon. The meson-cloud model gives definite predictions for the asymmetry awaiting future experimental verification.

V. CONCLUSIONS

The violation of the Gottfried Sum Rule observed by NMC [2,3] together with negative Drell-Yan asymmetry measured recently [9] by the NA51 group at CERN give a support to the conclusion that the $SU(2)$ symmetry of the nucleon sea is violated. As discussed recently by Forte [16] there are two possible kinds of symmetry violations, called $SU(2)_Q$ and $SU(2)_I$. The first one is simply connected with the asymmetry of light sea antiquarks $\bar{u} - \bar{d}$ in the proton. The second is related to the violation of the proton-neutron isospin symmetry. There are no a priori reasons, except of customs of practitioners in deep-inelastic scattering, for either symmetry to be more fundamental. Both GSR violation and negative Drell-Yan asymmetry can in principle be explained by either $SU(2)_Q$ ($\bar{d} > \bar{u}$) or/and $SU(2)_I$ (more abundant neutron than proton sea) symmetry violation. Some theoretical arguments [16] suggest, however, that the violation of the $SU(2)_Q$ symmetry seems to be more probable. While at present models explaining the $\bar{u} - \bar{d}$ asymmetry have been constructed, no reliable models explaining the proton-neutron isospin symmetry violation exist. The proton-neutron symmetry violation can be expected on the basis of the bag models as due to the mass difference of the u and d quarks as well as the corresponding di-quark states. At present a reasonable results can only be obtained for the valence quarks [43], which, however, has no influence on the GSR violation and rather little effect for the Drell-Yan asymmetry at the experimentally measured $x \approx 0.2$.

The old concept of the meson cloud in the nucleon gives a natural explanation of the $\bar{u} - \bar{d}$ asymmetry. The essential parameters of the model – coupling constants – are well known from the low-energy physics. If the remaining parameters of the model (cut-off parameters of the vertex form factors) are fixed from the high-energy neutron and Δ^{++} production [27] then both the GSR violation and the Drell-Yan asymmetry can be well described. The same model gives also a good description of the neutron electric form factor [44]. In our model the virtual mesons influence the static properties of the nucleon (axial vector coupling constant [27], electromagnetic radii [44], etc.).

Our model has to be contrasted to the solution of Ball and Forte [45,46] where mesons are produced radiatively via modified Altarelli-Parisi equations. Therefore their approach predicts strong dependence of the Gottfried Sum Rule on the scale, in the range of intermediate Q^2 . In our approach the Gottfried Sum Rule is constant, at least in the leading logarithm approximation. It would be very important to test these two scenarios experimentally. A preliminary evaluation of the NMC data seems to support rather our model [47].

We have discussed possibilities to identify the $\bar{u}-\bar{d}$ asymmetry through the observation of the dilepton pairs in the hadronic collisions. The analysis of the present $\mu^+\mu^-$ pair creation data in proton-nucleus scattering is not conclusive. The rapidity slope, very sensitive to the flavour asymmetry, depends also on the valence quark distributions. The ratio of the cross section in proton-nucleus to that in proton-deuteron collision is compatible with symmetric sea quark distributions. However, the case of asymmetry concentrated at rather small x is not excluded. The meson cloud model gives results compatible with the E772 Fermilab experimental data [10]. Elementary nucleon-nucleon Drell-Yan processes seem to be much better suited to study the $\bar{d}-\bar{u}$ asymmetry.

The presence of virtual mesons in the nucleon, especially pions, can explain the new result of the NA51 group at CERN for the Drell-Yan asymmetry. The Drell-Yan asymmetry is a quantity fairly insensitive to the valence quark distribution and very sensitive to the flavour asymmetry of the sea. The Drell-Yan asymmetries obtained with different valence quark distributions and symmetric sea are similar and positive. The meson cloud model predicts negative A_{DY} , which is consistent with the only existing experimental data point [9]. Furthermore it gives definite prediction for the x dependence of the flavour asymmetry, awaiting experimental verification. The new experiment planned at Fermilab [14] will open such a possibility.

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REFERENCES

- [1] K. Gottfried. *Phys. Rev. Lett.* **18** (1967) 1174.
- [2] P. Amaudruz *et al.* *Phys. Rev. Lett.* **66** (1991) 2712.
- [3] M. Arneodo *et al.* *Phys. Rev.* **D50** (1994) R1.
- [4] B. Badelek and J. Kwieciński. *Nucl. Phys.* **B370** (1992) 278.
- [5] V.R. Zoller. *Z. Phys.* **C54** (1992) 425.
- [6] H. Khan and P. Hoodbhoy. *Phys. Lett.* **B298** (1993) 181.
- [7] W. Melnitchouk and A.W. Thomas. *Phys. Rev.* **D47** (1993) 3794.
- [8] L.P. Kaptari and A.Yu. Umnikov. *Phys. Lett.* **B272** (1991) 359.
- [9] A. Baldit *et al.* *Phys. Lett.* **B332** (1994) 244.
- [10] A. Szczurek, J. Speth and G.T. Garvey. *Nucl. Phys.* **A570** (1994) 765.
- [11] H. Holtmann, N.N. Nikolaev, J. Speth and A. Szczurek. *Jülich preprint KFA-IKP(TH)-14* (1994) submitted to *Z. Phys. A*.
- [12] A.S.Ito *et al.* *Phys. Rev.* **D23** (1981) 604.
- [13] M. Ericson and A.W. Thomas. *Phys. Lett.* **B148** (1984) 181.
- [14] G.T. Garvey *et al.* *FNAL proposal, P866* (1992) .
- [15] P. Amaudruz *et al.* *Phys. Lett.* **B292** (1992) 159.
- [16] S. Forte. *Phys. Rev.* **D47** (1993) 1842.
- [17] Bo-Qiang Ma, A. Schäfer, W. Greiner. *Phys. Rev.* **D47** (1993) 51.
- [18] G. Altarelli and G. Parisi. *Nucl. Phys.* **B126** (1977) 298.
- [19] D.A. Ross and C.T.Sachrajda. *Nucl. Phys.* **B149** (1979) 497.

- [20] E.M. Henley and G.A. Miller. *Phys. Lett.* **B251** (1990) 453.
- [21] A. Signal, A.W. Schreiber and A.W. Thomas. *Mod. Phys. Lett.* **A6** (1991) 271.
- [22] W. Melnitchouk, A.W. Thomas and A.I. Signal. *Z. Phys.* **A340** (1991) 85.
- [23] S. Kumano. *Phys. Rev.* **D43** (1991) 59.
- [24] W-Y.P. Hwang, J. Speth and G.E. Brown. *Z. Phys.* **A339** (1991) 383.
- [25] V.R. Zoller. *Z. Phys.* **C53** (1992) 443.
- [26] A. Szczurek and J. Speth. *Nucl. Phys.* **A555** (1993) 249.
- [27] H. Holtmann, A. Szczurek and J. Speth. *Jülich preprint KFA-IKP(TH)-25* (1994) submitted to *Phys. Rev.* **D**.
- [28] S.D. Ellis and W.J. Stirling. *Phys. Lett.* **B256** (1991) 258.
- [29] P.L. McGaughey *et al.* *Phys. Rev. Lett.* **69** (1992) 1726.
- [30] A.D. Martin, W.J. Stirling and R.G. Roberts. *Phys. Rev.* **D50** (1994) 6734.
- [31] H. Holtmann, A. Szczurek and J. Speth. *Jülich preprint KFA-IKP(TH)-1993-33*,
- [32] T.D. Cohen and D.B. Leinweber. *Comments Nucl. Part. Phys.* **21** (1993) 137.
- [33] J.D. Sullivan. *Phys. Rev.* **D5** (1972) 1732.
- [34] P.J. Sutton, A.D. Martin, R.G. Roberts and W.J. Stirling. *Phys. Rev.* **D45** (1992) 2349.
- [35] W-Y.P. Hwang and J. Speth. *Phys. Rev.* **D46** (1992) 1198.
- [36] H. Holtmann, A. Szczurek and J. Speth. *paper in preparation* .
- [37] W.C. Leung. *Phys. Lett.* **B317** (1993) 655.
- [38] S.R. Mishra *et al.* *Phys. Rev. Lett.* **24** (1992) 3499.
- [39] S.D. Drell and T.M. Yan. *Ann. Phys.* **66** (1971) 578.

- [40] J.F. Owens. *Phys. Lett.* **B266** (1991) 126.
- [41] A.D. Martin, W.J. Stirling and R.G. Roberts. *Phys. Lett.* **B306** (1993) 145.
- [42] D.M. Alde *et al.* *Phys. Rev. Lett.* **64** (1990) 2479.
- [43] E.N. Rodionov, A.W. Thomas and J.T. Londergan. *Mod. Phys. Lett.* A9 (1994) 1799.
- [44] H. Holtmann, A. Szczurek and J. Speth. *Jülich preprint KFA-IKP(TH)-1994-33*, submitted to *Z. Phys.* **A**.
- [45] R.D. Ball and S. Forte. *Nucl. Phys.* **B425** (1994) 516.
- [46] R.D. Ball, V. Barone, S. Forte, M. Genovese. *Phys. Lett.* **B329** (1994) 505.
- [47] A. Brüll. Habilitationsschrift, Heidelberg 1995.

FIGURES

FIG. 1. The x -dependence of $F_2^{ep}(x) - F_2^{en}(x)$. The solid line was obtained including the effect of virtual mesons. The data points at $Q^2 = 4 \text{ (GeV/c)}^2$ are taken from Ref. [3].

FIG. 2. The total sea quark distribution $x(\bar{u}(x) + \bar{d}(x) + \bar{s}(x))$ obtained from our model. The solid line is the result of the full calculation, i.e. including the sea quarks in the bare nucleons (see Eq. 19). For comparison by the dashed line we show result obtained when neglecting the sea quark distribution in the bare baryons (mesonic contribution). The experimental data was taken from [38].

FIG. 3. The K -factors for the dilepton production in pp (solid line) and pn (dashed line) collisions for two different leading order quark distributions taken from [40] and [41].

FIG. 4. The cross section $M^3 d^2\sigma/dx_F dM$ for the production of the dilepton pairs in the proton-deuteron collisions. Shown is the fit of the K -factors for various quark distributions to the experimental data [29].

FIG. 5. The Drell-Yan ratio defined by Eq.(13) for iron and tungsten. The solid line is the result of our model, the dashed line the $MSR(A)$ parametrization and the dash-dotted line the $MSR(S'_0)$ parameterization.

FIG. 6. The effect of the $\bar{u} - \bar{d}$ asymmetry on the slope of the rapidity distribution. The two solid lines were calculated with the asymmetric quark distribution of the recent $MRS(A)$ quark parameterization [30] and that obtained from our model (MCM) [31,27,36]. The dashed lines were obtained using the symmetrization procedure (see Eq. 23). The arrows show the effect of the symmetrization in both cases.

FIG. 7. The slope of the rapidity distribution. The solid line is the result of our model [36]. The dotted line is the result obtained with the Owens parameterization [40], the dashed line was obtained with the $MRS(A)$ parameterization [30] with $\bar{d} - \bar{u}$ asymmetry and the dash-dotted line was obtained using the $MRS(S'_0)$ (symmetric) distribution.

FIG. 8. A two-dimensional map of the Drell-Yan asymmetry as a function of x_1 and x_2 . Shown are results obtained with the Owens parameterization [40] (left-upper corner), symmetric $MSR(S'_0)$ (right-upper corner), new $MRS(A)$ with the $\bar{u} - \bar{d}$ asymmetry built in (left-lower corner) and prediction of the meson cloud model [31,27,36] (right-lower corner). Note the change of the sign in the lower panels.

FIG. 9. The Drell-Yan asymmetry along the $x_1 = x_2$ diagonal. The meaning of the lines here is the same as in Fig.6. The experimental data point is taken from the recent result of the NA51 Collaboration at CERN [9].

FIG. 10. The $\bar{u}(x)/\bar{d}(x)$ ratio as obtained from the meson cloud model (solid line) [36] and the $MSR(A)$ parameterization (dashed line) compared with the experimental result of the NA51 collaboration [9].



















